An Alternative to Thermal Flux Measurements in UN Test 6(c)

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Abstract

In the United Nations' bonfire test (test 6c), thermal radiation measurements are used to determine the potential radiation hazards from transportation fires involving flammable substances. Currently, packaged substances are assigned to UN division 1.3 (propellants), if the irradiance from the bonfire test of the product exceeds 4 kw/m^2 at a distance of 15 m from the fire. The irradiance is measured over 5 seconds, during the period of maximum output. For substances, the value is corrected (scaled) to a mass of 100 kg net explosive content.

Thermal radiation measurements require complicated instrumentation, and are subject to significant errors introduced by wind, atmospheric attenuation, smoke obscuration, variation in source fire intensity, etc. Experience with UN test 6c, at the Bureau of Mines, indicates that the irradiance from bonfires involving typical test sample weights (10 to 100 kg) can be calculated to an acceptable degree of accuracy, from simple observations of the total burning time for the involved substance.

This paper discusses this simple approach, the current thinking of the UN Group of Experts on thermal flux measurements and criteria, and the impact of substituting burn times for thermal flux measurements on the classification of substances of interest.

Introduction

In conducting the United Nations external fire test (UN Test 6 (c)) it is necessary to make measurements of thermal radiation some distance from the bonfire. These measurements require complicated instrumentation, and are subject to significant errors introduced by wind, atmospheric attenuation, smoke obscuration, variations in source fire intensity, etc. In addition, radiation measurements of short duration fires are difficult to interpret in terms of the present criterion outlined in paragraph 44.4.4(c) of ST/SG/AC 10/11 (1). Paragraph (c) reads: if . . "the irradiance of the burning product exceeds that of the fire by more than 4 kW/m^2 at a distance of 15 m from the edge of the stack" . . . then the product, as packaged, is assigned to division 1.3 . . . "The irradiance is measured over 5 seconds, during the period of maximum output. For substances, the value is corrected to correspond to a mass of 100 kg net explosive content." For bonfire tests involving net explosives weights larger or smaller than 100 kg or for flux measurements made at distances other than 15 m a (mass)$^{2/3}$/(distance)^2 scaling

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law is ordinarily used to normalize (correct) the data. This scaling law is based on an assumed linear burning rate for the material under test with burning times scaling with the linear dimension of the stack or equivalently, the cube root of the mass. Size scaling presents no serious problem but it is likely that the assumption of a linear burning rate would break down for rapid burning propellants which ordinarily create fireballs and are consumed in very short times that do not strongly depend on the total involved mass. However, even in the case of very rapidly burning materials that produce fireballs, the radius of the fireball is, to a very good approximation, proportional to the cube root of the mass (2, 3). This again leads to a $m^{2/3}/R^2$ scaling law. The proper classification of rapid burning propellants is not a problem except when the observed burn time (for small samples) is significantly less than 5 seconds. In this case, averaging the flux over 5 seconds, as suggested in paragraph 44.4.4(c) results in a flux value well below the peak value and leads to some ambiguity in interpreting the test results. This has been pointed out in a recent paper submitted by the Netherlands for consideration by the United Nations Group of Experts (4). A proposal for reducing the thermal flux criterion in 44.4.4(c) from 4 kW/m^2 to 1.5 kW/m^2 at 15 m is also contained in this paper; adoption of the revised criterion could have significant impact on the current classification of some oxidizers and flammable solids.

The Bureau of Mines has been conducting research on the development of UN tests and criteria for a number of years under the sponsorship of the Department of Transportation and more recently under an agreement with the Department of Defense Explosives Safety Board. Some of this research involved measurements of thermal flux from burning propellants and flammable liquids and solids. Our experience in this area suggests that the irradiance from bonfires involving typical UN test sample weights (10 to 100 kg) can be calculated to an acceptable degree of accuracy from simple observations of the total burning time for the involved substance.

Experimental Results

Table 1 summarizes radiation measurements and observed burning times for a number of substances.

Table 1.--Measured and Calculated Values of Irradiance

Substance	Quantity kg.	Burn Time, s	Irradiance, kw/m^2 Measured	Irradiance, kw/m^2 Calculated
Nitrocellulose alcohol-wet	13.6	220	0.25 at 5 m	0.28 at 5 m
Nitrocellulose, plasticized	13.6	54	1.13 at 5 m	1.11 at 5 m
Pistol powder	13.6	15	3.4 at 5 m	4.0 at 5 m
Propellant mix	11.2	8	0.92 at 15 m	0.67 at 15 m
Nitrocellulose, plasticized	100	110	0.67 at 15 m	0.45 at 15 m

With the exception of the last entry (100 kg NC) the substances were contained in cylindrical cardboard containers having a length/diameter ratio of approximately 1.0; the 100 kg of plasticized nitrocellulose was contained in a standard 55 gallon (208 l) steel drum. All samples were ignited with 10 g of FFFg black powder placed just below the top surface of the substance. None of the containers were equipped with lids; so confinement was minimal.

Radiation measurements were made with heat flux gages obtained from Thermogage, Inc. (5). The irradiance values in table 1 represent average values obtained with three gages placed in a circular array (90° apart) at a ground height corresponding to the top of the sample containers and at the distances noted in table 1. Burning times were estimated from video camera records of the experiments. The burn times in table 1 correspond to the most intense burning and do not include the residual burning of the cardboard containers.

The values of irradiance listed in the right-hand column of table 1 were calculated from the equation:

$$I = \frac{C \cdot E}{4\pi R^2 t} \qquad \text{where,}$$

I = irradiance in kw/m^2,
C = constant = 0.33,
E = total energy content in joules,
R = distance from fire to gage position in meters,
t = observed burn time in seconds.

In applying the above equation, several assumptions were made. The first assumption involves calculating the total energy content of the test substance, E. The irradiance values in table 1 were calculated assuming a heat of combustion of 4186 J/g (1000 cal/g) for all the substances listed. This would appear to be a reasonable value for most substances capable of burning in the monopropellant mode. Other substances (coal, wood, liquid fuel) have much higher heats of combustion, but burn at much lower rates because of the limited availability of oxygen. These substances (flammable, solids or liquids) would not produce irradiance values high enough to be of concern here.

The second assumption involves the choice of the numerical value of the constant, C, in the above equation. This is the fraction of the total energy converted to thermal radiation. The vast majority of radiation measurements from combustion experiments indicate that the value of C lies between 0.2 and 0.4 (6); a value of 0.33 was chosen for the calculations in table 1. In applying the above equation it is also implicitly assumed that the mass consumption rate (E/t) is constant for a given material and packaging; for the experiments reported here, using a black powder igniter and minimal confinement, this was generally true.

Discussion & Conclusions

As can be seen from table 1, the calculated values of irradiance agree reasonably well with the measured values. This suggests that observed burning times could be used as a criterion for delineating 1.3 substances from 1.4 substances, probably with more confidence than can be placed in radiation measurements with all the vagaries associated with this type of measurement. The substitution of burning time for the irradiance criterion in paragraph 44.4.4(c) is an easy matter; 4 kW/m^2 for 100 kg at 15 m equates to a burn time of 12.2 seconds using the equation with the numerical values C and E discussed above.

This criterion eliminates the problems associated with making irradiance measurements and also eliminates the problem of time averaging for small quantities of material with burning times less than 5 seconds. For net masses other than 100 kg, burning times would scale as $M^{1/3}$ in keeping with the $M^{2/3}/R^2$ rule for scaling irradiance. Thus, for a 10,000 kg (22,000 lbs) cargo the value of 12.2 seconds for 100 kg net mass would scale to $(100)^{1/3} \times 12.2 = 56.6$ seconds.

Recent external fire tests with ammonium perchlorate (AP) in 55 gallon drums yielded heat flux values of 2.8 kW/m^2 at 15 m for 100 kg (220 lbs) of material (7). This value is well below the current UN criterion of 4 kW/m^2 at 15 m for 100 kg net mass; however, it is above the value of 1.5 kW/m^2 proposed in reference (4) indicating that AP might not meet the newly proposed criterion when packaged in 55 gallon drums. Larger scale tests with 25,000 lbs (11,363 kg) of AP in aluminum tote bins were also performed but radiation measurements were not obtained due to difficulties with instrumentation. Using the burning time scaling relationship discussed in this paper the scaled burn time for 25,000 lbs of AP is 59.1 seconds. Television records of the 25,000 lb burn showed that the actual burning time was considerably longer than 59.1 seconds indicating that AP in the tote bin configuration would pass the current UN criterion for thermal flux. However, reducing the flux criterion to 1.5 kW/m^2 as suggested in reference (4) might jeopardize the current classification of AP as an oxidizing substance when shipped in this configuration. (A thermal flux criterion of 1.5 kW/m^2 for 100 kg net mass corresponds to a 157.6 second burn time for 25,000 lbs).

Under conditions of light confinement and with a modest ignition source, plasticized nitrocellulose produced thermal flux values well below the current criterion of 4.0 kW/m^2 and even lower than the proposed 1.5 kW/m^2 for 100 kg net mass (last line table 1). Thus, properly packaged, this material is capable of passing the UN external fire test. However, packaging is crucial in determining the outcome of this test and it is not possible to predict the outcome of UN Test 6(c) on the sole basis of burning rate measurements on the unpackaged substance. This does not detract from the main theme of this paper: that observations of burning times in UN Test 6(c) could be used in place of thermal flux measurements for delineating propellant-like materials from flammable solids or oxidizers.

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